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THERMAL SHOCK: AN ANNOTATED BIBLIOGRAPHY

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Lockheed

MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

ABSTRACT

The search made began with the literature of 1956. Glenny ~~(21)~~ in 1961 and Majors ~~(37)~~ in 1957 have written extensive review articles concerning thermal fatigue. Some of the references ~~in~~ of these ~~articles~~ authors apply directly or are related to the subject of this bibliography.

This search was oriented toward aiding ~~LMSC~~ researchers in developing a definition for thermal shock (there are conflicts in the literature) and in studying thermal shock vs. fatigue cycling.

Search completed August 1962.

Availability notices and procurement instructions following the citations are direct quotations of such instructions appearing in the source material announcing that report. The compiler is well aware that many of these agencies' names, addresses and office codes will have changed; however, no attempt has been made to update each of these notices individually.

In citing classified reports, (SECRET TITLE) or (CONFIDENTIAL TITLE) as appropriate, has been used when that classification of the title was indicated on the report. (UNVERIFIED TITLE) has been used when the report was not available to the compiler and it was impossible to verify the report's title and the title's security level.

Classification of classified reports is indicated by abbreviation in upper right top line of bibliographic entry. The classification of the report is given in full, e.g., SECRET REPORT, at the conclusion of the bibliographic data for that report entry.

This selective bibliography has been prepared in response to a specific request and is confined to the limits of that request. No claim is made that this is an exhaustive or critical compilation. The inclusion of any reference to material is not to be construed as an endorsement of the information contained in that material.

1. Bal'shin, M. Yu. and Huei, T.S.

CERTAIN PROBLEMS OF THERMAL STABILITY. Foreign Tech. Div., Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. 3 Nov 1961, 9p. ASTIA AD-266 760. (Trans. no. FTD-TT-61-160 of IZVEST. AKAD. NAUK S.S.S.R., OTDEL. TEK. NAUK, MET. i TOP. v. 3, p. 73-76, 1961.)

The mechanism of the phenomena which arise in a solid as a result of cyclic heat treatment with rapid changes in temperature was studied. The conductivity of graphite with and without impregnated bakelite was measured to evaluate the thermal stability of the materials during heat treatment. It was confirmed experimentally that during cyclic heat treatment, the internal stresses associated with temperature variations caused a decrease in the contact surface. Compressive stresses associated with minute cavities in solids containing dispersed particles decreased electrical resistance and increased the contact surface. The thermal stability of a solid is determined by the properties, size, and shape of the material. Surface films can increase the thermal stability of a solid.

2. Baron, H.G. and Bloomfield, B.S.

RESISTANCE TO THERMAL FATIGUE CRACKING OF SEVERAL TYPES OF CAST IRON. Armament Research and Development Establishment (Gt. Brit.). ARDE Memo. no. (MX) 53/61, Oct 1961, 14p. ASTIA AD-265 818.

Cracking was produced in test pieces of chilled white iron, engineering grey iron and two casts of nodular iron, by repeated heating of one edge of the specimen while the mass of the specimen was water cooled. The white iron gave extensive cracks when heated to 650° C, but survived several thousand cycles of 40 - 450° C due to its high compressive strength. The grey iron gave a fatigue curve lying between the white

2. (cont'd) and nodular irons over much of the temperature range, but with the low temperature cycle of 40 - 500° C it showed greater resistance to cracking than the nodular irons. This unexpected result is attributed to the low elastic modulus of grey iron. The nodular irons were comparable with plain carbon steels in their resistance to cracking. In low temperature tests they were slightly more resistant to cracking in the as-cast state than after annealing to produce a ferrite matrix. With cycles at 40 to 850° C or to 1000° C the annealed material was better.

3. Bollenrath, F.

BEMERKUNGEN ZUR FRAGE DES WARME-SCHOCKS IM FLUGZEUGBAU. Westdeutscher Verlag, Köln & Opladen. (NATO AGARD Gen. Assembly, Brussels, 27 Aug 1956.) DVL Bericht n. 30, June 1957, 24p. (In German)

Study of the thermal shock problem in aircraft structures. The case of a plate between two high-speed flows (one hot, one cold gas) is considered. Pressure distribution dependent on time and plate thickness is calculated for various structural materials.

4. Bollenrath, F.

SOME REMARKS UPON THE PROBLEM OF TEMPERATURE SHOCK IN AIRCRAFT. AGARD rept. no. 90, Aug 1956, 12p.

Structural problems, particularly thermal shock, associated with nonuniform, transient temperatures in structural members are discussed in general. The temperature distribution in a thick plate heated on one surface and cooled on the other by forced convection is calculated and resulting thermal stresses are determined for two types of restraint.

5. Boley, B.A. and Weiner, J.H.

THEORY OF THERMAL STRESSES. New York, John Wiley & Sons, 1960, 569p.

Includes basic theory with mechanical and thermodynamic foundations. Heat conduction and thermal stress analysis are discussed for elastic and inelastic systems.

6. Clauss, F. J. and Freeman, J. W.

THERMAL FATIGUE OF DUCTILE MATERIALS.

I. EFFECT OF VARIATIONS IN THE TEMPERATURE CYCLE ON THE THERMAL-FATIGUE LIFE OF S-816 AND INCONEL 550. National Advisory Committee for Aeronautics, Washington, D.C. NACA Technical note no. TN-4160, Sep 1958, 61p. ASTIA AD-204 882.

The experimental results indicated that the maximum cycle temperature had more effect than the temperature difference on the number of cycles to failure. Increasing the cycle time of exposure at the maximum cycle temperature improved the thermal-fatigue life at high maximum cycle temperatures, whereas the same increase in exposure time at low maximum cycle temperatures decreased the number of cycles to failure. The number of cycles to failure depends upon temperature and time effects in addition to the thermal strains absorbed by plastic flow.

7. Clauss, F. J.

Thermal fatigue of ductile materials. _In_ FOURTH SAGAMORE RESEARCH CONFERENCE ON HIGH TEMPERATURE MATERIALS, THEIR STRENGTH POTENTIALS AND LIMITATIONS, PROCEEDINGS. Racquette Lake, N.Y., 21-23 Aug 1957. (Co-sponsored by the Ordnance Materials Research Office and the Office of Ordnance Research of the U.S. Army) p. 175-192, 1957. OTS, PB 131834.

Describes a fundamental study of thermal fatigue in ductile alloys. The effects of cyclic temperature variables on thermal fatigue are discussed. The extent of changes in the stress-rupture strength and ductility caused by varying amounts and conditions of thermal fatigue prior to fracture is evaluated. Experimental observations on thermal fatigue behavior are explained on the basis of present theories of the solid state.

8. Clements, J.F. and Vyse, J.

Sonic spalling test. II. Assessment of the effect of thermal shock. Great Britain. GAS COUNCIL RESEARCH COMMUNICATION GC 39, p. 27-33, 1957.

The response of fireclay products to thermal shock can be separated into the following properties: a tendency to crack during heating or cooling, and a tendency to break after cracking.

9. Coffin, L.F., Jr.

Strain cycling and thermal stress fatigue. In FOURTH SAGAMORE RESEARCH CONFERENCE ON HIGH TEMPERATURE MATERIALS, THEIR STRENGTH POTENTIALS AND LIMITATIONS, PROCEEDINGS. Racquette Lake, New York, 21-23 Aug 1957. (Co-sponsored by the Ordnance Materials Research Office and the Office of Ordnance Research of the U.S. Army). p. 219-260, 1957. OTS, PB 131,834.

10. Coffin, L.F., Jr.

Thermal stress and thermal fatigue. PROC. SOC. EXPTL. STRESS ANAL. v. 12, n. 2, p. 117-130, 1958.

The author reviews thermal-stress effects observed in ductile metals and describes experiments in which parameters of thermal-stress fatigue arising from the constraint of thermal expansion were determined. Results for the effects of the temperature range, cold working, mean temperature, and speed of cycling on thermal-stress fatigue are given. The significance of the plastic-strain range and its relation to cycles to failure is discussed.

11. Coffin, L.F., Jr.

Thermal stress fatigue. PROD. ENG.

v. 28, p. 175-179, June 1957.

Discusses the differences between mechanical and thermal fatigue, the origin of thermal stresses, the role of thermal cycling in fatigue, and defines thermal shock parameters.

12. Davis, J.E., et al

INVESTIGATION INTO MORE COMPLETE USE OF STRUCTURAL MATERIALS THROUGH A STUDY OF THE STRESS-TEMPERATURE-TIME CONDITIONS OF A RE-ENTRY VEHICLE. Douglas Aircraft Co., Inc., Santa Monica, Calif. Rept. for July 1959-May 1960 on Metallic Materials. WADD TR 60-363, Nov 1960, 239p. (Contract AF 33(616)6680, Proj. 7351) ASTIA AD-249 787.

In the past, vehicles operated in a fairly low temperature environment. The selection of materials were primarily dependent on the quasi-static and dynamic loads. With the advent of manned hypersonic glide re-entry vehicles, the temperature and time parameters were found to significantly affect the selection of materials. In this report the criteria for including the effects of temperature and time are clarified by using six measuring sticks. Two materials, Inconel 718 and Haynes 25 were evaluated for repeated exposure to a typical hypersonic re-entry glide trajectory.

13. Delmas, R.

Behavior of heat-resistant materials for turbine nozzles under thermal shock. JAHRBUCH WISSENSCHAFT. GESELLSCH. LUFTFAHRT p. 190-197, 1958.

13. (cont'd) The test consisted of heating the trailing edge of nozzles with controlled propane flame and then cooling with an air blast. The temperature cycling range was from 250 to 1150° C; heating and cooling times were 55 and 26 secs, respectively. The materials investigated were gas turbine metallic alloys and cermets. Elastic analyses of stresses for both temperature gradient through thickness and along length of nozzle were made on basis of flat plate.

14. DeVries, D.

How corn products licked thermal shock proolem.

PLANT ENG. v. 13, n. 2, p. 94-95, 1959.

Ambient air at 90° F and combustion gases at 1600° F caused thermal shock, stress cracking and high temperature corrosion in a flash dryer used for processing grain sorghums into several products. Hastelloy X was used to overcome the problems and resulted in excellent strength and corrosion resistance.

15. Dolan, T.J.

Basic research in fatigue of metals. A.S.

T.M., BULL. n. 240, p. 24-27,

1959.

Contains a summary of the findings of ASTM Research Subcommittee of Committee E-9 on fatigue. The extent of present knowledge is outlined and different types of basic research are discussed. Recommendations for concentrated research efforts are included.

16. Dugdale, R.A.

THERMAL-SHOCK AND THERMAL-STRESS

FATIGUE IN A STABILIZED PINCH-FUSION

REACTOR. U.K. Atomic Energy Authority

Publ. no. R.2955, 1959, 14p.

An estimate of the temperature difference developed across the reaction-chamber wall and the resultant stresses and strains set up is used to predict conditions which would produce cracking of the wall.

17. Francois, M.

Study of thermal shock in refractories. CHALEUR & INDUSTRIE v. 37, p. 143-158, 195-207, 1956.

Non-cyclic study. The refractory face is heated with a standard gas flame. Cracks are observed as they occur during cooling.

18. Freudenthal, A.M. and Weiner, J.H.

On the thermal aspect of fatigue. J. APPL. PHYS. v. 27, n. 1, p. 44-50, 1956.

A theoretical discussion of fatigue phenomena is presented and a mechanism of fatigue-crack initiation within glide bands is expounded. The highly localized temperature and associated thermal-stress gradients in front of active slip-planes are postulated to be sufficiently severe to account for the initiation of micro-cracks parallel to the slip planes, provided that slip under repeated stress is concentrated into striations. The concept avoids difficulties associated with earlier theories of strain-hardening. The effect of the thermal characteristics of a metal on its fatigue performance is discussed with particular reference to commercially pure Al and Al alloy 24S-T.

19. Gatewood, B.E.

THERMAL STRESSES. New York, John Wiley & Sons, 1957, 232p.

Includes some information on thermal shock.

20. Gilbey, D.M.

Theory of thermal stresses. J. LESS COMMON MET. v. 1, n. 2, p. 139-144, 1959.

Discusses an extension of the theory of thermal streses which allows the "constants" of thermal conductivity, thermal expansion, Young's modulus, and Poisson's ratio to vary with temperature. The data needed include sufficient stress/strain curves at different temperatures and the variation of thermal conductivity and thermal expansion with temperatures. Thermal stress calculations are programmed for a computer.

21. Glenny, E.

Thermal fatigue. MET. REV. v. 6, n. 24,

p. 387-465, 1961.

Defines various aspects of the problem, and concludes that the primary causes of failure are due to cyclic strain fatigue, cyclic creep or corrosion-fatigue. Each application must be given individual treatment. The increasing complexity of service conditions has brought about a need for closely simulative testing. 170 references are included.

22. Glenny, E. and Royston, M.G.

TRANSIENT THERMAL STRESSES PROMOTED BY THE RAPID HEATING AND COOLING OF BRITTLE CIRCULAR CYLINDERS. National Gas Turbine Establishment, Gt. Brit. Rept. no. R.226, July 1958, 46p.

Investigation of the validity of the theory for calculating transient thermal stresses. A high alumina ceramic is tested with hot and cold fluidized beds as heating and cooling media. The agreement between experiment and theory is reasonable considering the nonstatistical nature of the experiments and the assumptions involved in developing and using the theory, as well as in correlating the thermal stress to failure with breaking strength.

23. Glenny, E., et al

A technique for thermal-shock and thermal-fatigue testing based on the use of fluidized solids.

J. INST. METALS v. 87, p. 294-302, 1959.

Describes laboratory tests for studying the behavior of materials under conditions of transient thermal stress such as might arise in gas turbine blades. The specimen is immersed in a bed of powered refractory substance supported on a permeable plate and fluidized by a stream of air.

24. Hetnarski, R.

Coupled one-dimensional thermal shock problem for small times. ARCHIWUM MECHANIKI STOSOWANEJ v. 13, n. 2, p. 295-306, 1961. (In Polish)

A generalized heat equation coupled with elastic deformation is presented. The equation must be considered only for dynamic problems because in a static case, the coupling effect vanishes.

25. Hillier, M.J.

Correlation of thermal stresses in circular cylinders and flat plates. ENGINEER v. 207, n. 5372, p. 56-57, 1959.

Published data concerning the production of a stress system within hollow cylinders, which are lagged on the inner face because of a steep change in fluid temperature adjacent the metal surface, are reworked on a common base and compared.

26. Hoff, N.J. (ed.)

HIGH TEMPERATURE EFFECTS IN AIRCRAFT STRUCTURES. (AGARDograph no. 28) New York, Pergamon Press, Inc. 1958, 357p.

Contains 16 summaries of fields which enter into the analysis of thermal problems arising from aerodynamic heating. Information on high temperature fatigue and thermal stresses is included.

27. Kennedy, C.R.

Plastic strain absorption as a criterion for high temperature design. In FOURTH SAGAMORE RESEARCH CONFERENCE ON HIGH TEMPERATURE MATERIALS, THEIR STRENGTH POTENTIALS AND

27. (cont'd) LIMITATIONS, PROCEEDINGS. Racquette Lake, N.Y., 21-23 Aug 1957. (Co-sponsored by the Ordnance Materials Research Office and the Office of Ordnance Research of the U.S. Army). p. 193-219, 1957. OTS, PB 131,834.

The development of isothermal strain reversal data as an aid to high temperature design is proposed. A test apparatus capable of mechanically cycling a specimen in tension and compression within set strain limits is described. Data are presented which confirm Coffin's theory that total plastic strain per cycle can be used to predict the number of cycles to failure. Evidence that Inconel strain weakens at the test temperature is noted and grain size is found to be the most important variable affecting the behavior of materials subjected to strain reversals.

28. King, D.F. and Walther, F.H.
Rotary hearth furnace for testing resistance of refractories to thermal shock. BULL. AM. CERAM. SOC. v. 40, n. 7, p. 456-459, 1961.

The furnace is equipped with automatic motor-driven rotation, is gas fired with open air cooling, and operates easily on a 2400-1000° F cycle. Tests on a wide range of refractory materials showed much variation in their ability to resist thermal shock.

29. Kostochkin, Yu. V. and Oding, I.A.
Susceptibility of metals to damage during thermal fatigue. IZVEST. AKAD. NAUK S.S.S.R., MET. I TOPL (TEKHN.) v. 1, p. 101-104, 1960. (In Russian)

Experiments were carried out on a Ni-Cr alloy EI-765 and an austenitic steel EI-612 used for gas-turbine blades. Samples were heated in a current of hot gas at 750° C and cooled to 70° C to simulate actual working conditions. Tests for creep resistance were made. An increase in the number of thermal cycles resulted in a shorter life on test. The rate of reduction in life was retarded with an increase in the number of cycles. Final fracture occurred when the crack was half way across the specimen, by transcrystalline cracking as in a tensile test. The failure of a specimen not

29. (cont'd) subjected to thermal cycling occurred simultaneously across the entire section by intercrystalline cracking. Micro-damage caused by thermal cycling has little effect in a tensile test but develops into macro-cracks during creep testing. Creep testing is, therefore, a convenient method of showing up the damage caused by thermal cycling.

30. Lauchner, J.H. and Bennett, D.G.

Thermal fracture resistance of ceramic coatings applied to metal; I. Elastic deformation. J. AM. CERAM. SOC. v. 42, n. 3, p. 146-50, 1959.

Four cobalt-bearing ground-coat type coatings applied to enameling grade iron specimens were studied. Indications were that after receiving a given thermal treatment, ceramic coatings fracture when subjected to thermal shock by a critical temperature differential. Residual compressive stress in a coating is a major factor in improved thermal shock resistance. Increased resistance to thermal shock is gained by decreasing coating thickness.

31. Lauchner, J.H., et al

Effect of firing schedules on stress-temperature relations in enamel-metal systems. J. AM. CERAM. SOC. v. 40, n. 12, p. 410-415, 1957.

Cooling rates affect development of thermal stresses. Residual compressive stresses in enamel are increased by rapid cooling from firing temperatures.

32. Laval, J.

Thermal stresses in a crystalline array. J. PHYS. RADIUM v. 20, n. 6, p. 577-588, 1959.

Thermal stresses as a function of temperature are estimated. At low and intermediate temperatures, they are directly proportional to the square of the average quadratic amplitudes of the fundamental thermal oscillations.

33. Lazarev, G. P.
Machine for testing the thermal fatigue of materials. ZAVOD. LAB., S.S.S.R. v. 25, n. 3, p. 357-358, 1959. (In Russian)

34. Lessen, M.
Thermoelasticity and thermal shock. J. MECH. AND PHYS. SOLIDS v. 5, n. 1, p. 57-61, 1956.

The problem of "initial" thermal shock is formulated and the solution is found to be similar to that of a Fourier equation with modified diffusivity.

35. L'vovskii, M. Ia. and Smiian, I. A.
A new method for testing the resistance to thermal shock of heat-resistant sheet materials. INDUST. LAB. v. 24, n. 2, p. 213-215, Mar 1959. (Translation of ZAVOD. LAB. SSSR v. 24, n. 2, p. 202-203, Feb 1958 by Instrument Soc. Amer., Pittsburgh 22, Pa.).

The authors give a brief account of the technique for measuring the comparative resistance of sheet materials to thermal shock. The specimen is in the form of narrow tapered strip 185 mm long with an accurate notch cut in center of wider end (20 mm wide). Equipment is provided to automatically retain the strip in an electric furnace until the temperature at the notched end (recorded by thermocouple on specimen) reaches a preset value. Strip then is dropped by the solenoid into a quench bath and the cycle repeated. Cycle time is approximately 1 min and 5 sec. End point of the test is when a crack spreading from the notch measures a fixed length. The apparatus is designed for metal testing.

36. Mahorter R.G., Jr.

COATINGS FOR MOLYBDENUM. Aeronautical Materials Lab., Naval Air Material Center, Philadelphia, Pa. Rept. no. NAMC-AML-1234, Summary rept. for Apr 1958 - Sep 1960, 1 May 1961, 16p. ASTIA AD-258 935.

The relative thermal shock resistance in air, under stress, of eight protective coatings were evaluated. The temperature cycle used was 1800° F to 200° F and the stress was 45,000 psi. Specimens were tested until failure or 500 cycles occurred. Specimens which performed well during the 1800° F to 200° F cycle were tested using a 2000° F to 300° F cycle.

37. Majors, H., Jr.

COMPARISON OF THERMAL FATIGUE WITH MECHANICAL FATIGUE CYCLING. Bureau of Engineering Research, Univ. of Alabama. Final Report, Sept 1957, 77p. (Contract DA-01-009-ORD-396 and DA-01-009-ORD-454). ASTIA AD-146 574.

Contains 45 references. Among the conclusions drawn were the following: In order to attempt a correlation of load cycling with thermal fatigue cycling, more data are needed for several mean temperatures; thermal cycling had a tendency to smooth the grain boundaries, thermal cycling under constant load displayed heavy inter-granular oxidation on the inner surfaces of the tubular specimens, and there was no influence on the coefficient of thermal expansion with cycles of thermal cycling under constant load.

38. Manson, S.S.

Thermal stresses in design. MACHINE DESIGN v. 30, n. 12, 13, 16, 17, 18, p. 114-20, 12 June 1958; p. 99-103, 26 June 1958; p. 100-7, 7 Aug 1958; p. 110-3, 21 Aug 1958; p. 126-33, 4 Sept 1958.

38. (cont'd) Discusses thermal shock in flat plates, quantitative determination of thermal shock parameters experimentally and thermal stress fatigue.

39. Manson, S.S. and Smith, R.W.

Quantitative evaluation of thermal-shock resistance.

TRANS. AM. SOC. MECH. ENGRS,

v. 78, n. 3, p. 533-544, Apr 1956.

Thermal shock resistance is dependent on two parameters: conductivity and the ratio of fracture stress to the product of the elastic modulus and the coefficient of thermal expansion.

40. Marin, J. (ed.)

MATERIALS ENGINEERING DESIGN FOR HIGH

TEMPERATURES. Pennsylvania State University.

University Park, Pa. (Proceedings of a short

course held at Pennsylvania State University,

30 June – 4 July 1958). 1958, 418p.

A short course was held with the objective of presenting current knowledge on the response of materials to elevated temperatures and how it can be applied to high temperature design. The problem of cyclic temperature fatigue is handled by Coffin in Chapter V which contains a discussion of current research on thermal fatigue. A method for conducting thermal fatigue studies is illustrated. The author shows the influence of prior cold work, stress and strain cycling, change in stress range, mean temperature, speed of cycling, plastic strain range, and in-phase relations between temperature and strain cycling, upon thermal fatigue. Extensive constant-temperature strain cycling tests were conducted because of the complex cyclic temperature tests. Other factors related to strain cycling are included, viz. strain localizing, cyclic strain-induced creep, and applications to design.

41. Meker, G.

Thermal shock testing machine. BULL. SOC.

FRANC. CERAM. n. 34, p. 19-25, 1957.

Includes test data.

42. Mendelson, A. and Manson, S.S.

Approximate solution to thermal-shock problems in plates, hollow spheres and cylinders with heat transfer at two surfaces. TRANS. AM. SOC. MECH. ENGS., v. 78, n. 3, p. 545-553, Apr 1956.

Transient thermal stresses are computed using a method which applies polynominal approximations to temperature distribution to a reduced partial differential equation of the problem to a set of first order ordinary differential equations.

43. Miller, D.R.

BIBLIOGRAPHY ON THERMAL STRESSES AND LOW CYCLE FATIGUE. Knolls Atomic Power Lab. Rept. no. KAPL 2048, 20 Aug 1959, 29p.

200 references.

44. Nariboli, G.A.

Spherically symmetric thermal shock in medium with thermal and elastic deformations coupled. QUART. J. MECH. AND APPL. MATH. v. 14, pt. 1, p. 75-84, Feb 1961.

Discusses the effect of thermoelastic coupling on the passage of a disturbance through an infinite medium with spherical cavity when its temperature is suddenly changed. The effect of coupling is to reduce the fluctuation of stress and the "shock" character of the disturbance.

45. Parkes, E.W.

A DESIGN PHILOSOPHY FOR REPEATED THERMAL LOADING. Advisory Group for

45. (cont'd) Aeronautical Research and Development, Paris, France. Rept. no. 213, Oct 1958, 24p. ASTIA AD-327 622.

Presented at the Eighth Meeting of the Structures and Materials Panel, held 20-25 Oct 58, in Copenhagen, Denmark. The problem of the stress associated with change of temperature occurs in civil and mechanical engineering and is there almost invariably overcome by permitting free thermal expansion. The idea of free thermal expansion can sometimes be applied in the newer branches of engineering, but in many cases this is not so — the thermal strains are resisted and thermal stresses result. The magnitude of these thermal stresses can be reduced by the use of insulation, or by combining materials having different properties, but even with these aids the stresses are likely to exceed the limit of elasticity of the material for quite small temperature changes. It follows that if full use is to be made of the high temperature materials we must design inelastically. Designing inelastically for one cycle of thermal loading is comparatively easy, but if the thermal loading is repeated a number of times, the structure may suffer from alternate plasticity (and possible strain fatigue) or from incremental collapse. The use of a safety factor applied to the stresses is unduly conservative, whereas the use of a safety factor applied to the loads may be dangerous. It is possible that the concept of a statistical safe time for the structure, based upon its expected load-temperature-time history, may have to be used. These various aspects of the problem are discussed in this report and illustrated with calculations for some simple models in which the load is kept constant and the temperature varied cyclically.

46. Pridantsev, V.M. and Krylova, A.R. A method of determining the resistance to thermal shock of sheet steels and alloys. INDUST. LAB. v. 24, n. 2, p. 216-218, Mar 1959. (Translation of ZAVOD. LAB., SSSR v. 24, n. 2, p. 204-205, Feb 1958 by Instrument Soc. Amer., Pittsburgh 22, Pa.)

An apparatus is described for thermally cycling a sheet specimen having an arbitrary size and configuration of holes and for measuring the number of heating and cooling cycles required to produce the first crack. This comparative test does not yield basic material properties. Tests on austenitic Cr-Ni steel indicate that the logarithm of the cycles to first crack decreases with an increase in temperature amplitude. Cycles to thermal fatigue failure also decrease as sheet thickness increases and grain size decreases.

47. Royston, M.G.

THE RELATION OF STRENGTH TO THE THERMAL SHOCK FAILURE OF BRITTLE MATERIALS. Gr. Britain, National Gas Turbine Establishment. Memorandum no. M.315, 6 Nov 1958, 17p. ASTIA AD-203 767.

It is possible to explain quantitatively the variation of strength of brittle materials with size and mode of stressing. By an extension of Weibull's theory (AD-76 790) a relation between bend strength and thermal fracture stress can be developed which permits the design of bend strength specimens that fail under conditions analogous to those of thermal shock.

48. Sadowsky, M.A.

THERMAL SHOCK ON CIRCULAR SURFACE OF EXPOSURE TO ELASTIC HALF SPACE. American Society of Mechanical Engineers. (Paper presented at a meeting on 28 Nov - 3 Dec 1954.) Paper no. 54-A-44, 6p.

Discusses a case in which part of a plane surface of a body is exposed to spontaneous radiation causing a finite amount of heat to become absorbed by the exposed part of the surface.

49. Serensen, S.V. and Kotov, P.I.

Methods of recording cyclically changing temperatures and stresses in thermal fatigue tests. ZAVOD LAB., S.S.S.R. v. 27, n. 8, p. 1013-1018, 1961. (In Russian)

50. Serensen, S.V. and Kotov, P.I.
Tests with cyclic thermal stresses of varying severity in the investigation of thermal fatigue. INDUST. LAB. v. 25, n. 10, p. 1272-1279, 1960. (Translated from ZAVOD. LAB., S.S.S.R. v. 25, n. 10, p. 1216-1233, 1959)

51. Sklyarov, N.M., et al.
Effect of thermal stresses on the short-time, long-time and vibration strength of alloys. SYMPOSIUM: ISSLED. PO ZHAROPR. SPLAV., MOSCOW, AKAD. NAUK SSSR v. 5, p. 39-41, 1959. (In Russian)

The effect of thermal stresses on short-time fracture, long-time tensile strength and fatigue strength was investigated. It has been established that, depending on the magnitude of the temperature drop and the mean temperature of the cycle, the number of cycles before fracture varies from a few cycles to 10^4 plus cycles. No single-valued relation between the heat resistance and the plasticity of the materials was detected.

52. Sternberg, E. and Chakravorty, J.G.
THERMAL SHOCK IN AN ELASTIC BODY WITH A SPHERICAL CAVITY. Brown Univ., Div. of Applied Mathematics, Providence, R.I. Technical rept. no. 3, June 1958, 27p. (Contract Nonr-56225) ASTIA AD-200 018.

This investigation aims at the dynamic thermoelastic response of an infinite medium with a spherical cavity to a sudden uniform change in the temperature of its internal boundary. By means of the Laplace transform, a closed solution to this problem – exact within classical elastokinetics - is obtained in terms of error functions of real and complex arguments. The ensuing temperature stresses are compared with the corresponding quasi-static results.

53. Sternberg, E. and Chakravorty, J.G.

Thermal shock in an elastic body with a spherical cavity. QUART. APPL. MATH. v. 17, n. 2, p. 205-218, July 1959.

The elastic response of an infinite medium containing a spherical cavity is analyzed for the case of an instantaneously applied uniform temperature change at the cavity wall. Numerical results show a pronounced oscillation of dynamic stresses at the inner boundary, and a propagating shock wave elsewhere, with a decreasing jump discontinuity as the wave-front progresses away from the cavity.

54. Weiss, V., et al

Thermal cycling under constant load to low temperatures of aluminum and magnesium alloys. In SYMPOSIUM ON LOW-TEMPERATURE PROPERTIES OF HIGH-STRENGTH AIRCRAFT AND MISSILE MATERIALS. ASTM STP no. 287. American Society for Testing Materials, Philadelphia. p. 37-50, 1961.

The effect of thermal cycling under constant stress on 7075-T6 and X2020-T6 Al alloys and AZ31B-H24 and Hk31A-H24 Mg alloys was investigated for sawtooth type cycling between -320° F. and maximum temperatures of 600° F. for the Al alloys and 400° F. for the Mg alloys.

55. White, J.

Some general considerations on thermal shock. TRANS. BRIT. CERAM. SOC. v. 57, n. 10, p. 591-611, 1958.

Two quantitative theories of brittle fracture are reviewed. The first assumes a brittle material remains elastic up to the point of fracture. In the second, a probability of fracture is assumed which depends on the volume of material stressed and the probability of Griffith cracks being activated. A theory of thermal shock in a two-phase

55. (cont'd) material is developed in which thermal stress is defined as a function of the expansion coefficient. Thermal stresses arising from anisotropy, and suggested explanations of expansion hysteresis are discussed also.

56. Yen, T.C.

THERMAL FATIGUE. Welding Research Council, England. Bulletin, Oct 1961, 12p.

Literature survey. Includes data on test procedures and fatigue life and stress rupture for experiments with 347 Stainless, Inconel 550, A302 steel and S-816 alloys at temperatures up to 1600° F.